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Improved Phase-locked Loop Scheme Using Half Period FFT under Distorted Three-Phase Grid Voltage

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Abstract. To maintain the synchronization between the inverter voltages with grid under distorted grid voltage condition, an improved phase-locked loop (PLL) method using the fast Fourier transform (FFT) algorithm with minimum sampling data is proposed in this paper. The proposed algorithm calculates the phase angle and the magnitude of harmonic components accurately under the balanced three phases grid voltage. Even if the grid voltage is distorted by harmonics or three phase voltages are unbalanced, the proposed scheme can effectively track the phase angle of grid voltage and calculate the magnitude of harmonic components perfectly within half period of grid voltage.

Keywords: Fast Fourier transform, Grid connected inverter, Phase locked loop.

1 Introduction

A conventional power generation system based on the thermal generator is one of the important sources of the carbon dioxide gas. To decrease the amount of emitting carbon dioxide gas, many researches have been done on renewable energy in recent years [1]. Distributed generation systems such as renewable energy are connected to the grid using a grid-connected inverter to supply active and reactive power. The active and reactive power flow can be adjusted by controlling the inverter currents in the synchronous reference frame. It is well known that the synchronization between the inverter and grid is essential to control the inverter output currents effectively in *dq*-axis. The computed voltage reference is applied through the space vector pulse width modulation (SVPWM) strategy because of the enhanced performance [2].

In order to operate the grid-connected inverter synchronously with grid voltage, the phase angle of grid voltage has to be obtained exactly without distortion. Since the incorrect phase angle due to the harmonic distortion in the grid voltage yields distorted inverter currents, the phase angle should be detected effectively with fast dynamics even if the grid voltage is distorted by harmonics [3]. However, the conventional phase detection method known as the synchronous reference frame phase-locked loop (SRF-PLL) gives performance degradation under distorted grid

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voltage. This scheme normally uses the standard proportional-integral (PI) control loop, resulting in slow dynamic response [4], [5].

To overcome this limitation, this paper proposes a novel phase-locked loop (PLL) algorithm based on the half-period fast Fourier transform (FFT) with minimized-sampling, which can effectively calculate each harmonic component with reduced sampling rates. To reduce the calculation time, the FFT algorithm based on the butterfly structure is selected to obtain the fundamental component of the grid voltage [6]. By using the proposed PLL algorithm, the accurate phase angle of grid voltage can be detected even if the grid voltage is highly distorted. The effectiveness of the proposed algorithm is proved through experimental results.

2 Proposed phase angle and harmonic detection algorithm

To detect the phase angle of grid voltage, three phase grid voltages are measured by using the voltage sensors. The measured three phase voltages are transformed to *dq* values through the Park's transformation. The obtained *d*-axis voltage is maintained to zero by the PI controller. The output of the PI controller generates the angular frequency of grid voltage. This value is integrated to determine the phase angle information, which is again used to calculate the *dq* values through the Park's transformation.

The minimized-sampling frequency for the FFT algorithm should be larger than the Nyquist frequency as follows:

$$f_s \geq f_{Nyq} = 2 \cdot f_{\max} = 2M \cdot f_1 \tag{1}$$

where f_s is the minimized-sampling rate for the FFT algorithm, f_{Nyq} is the Nyquist frequency, $f_{\max}$ is the highest frequency, M is the highest harmonic order in grid voltage, and f_1 is the fundamental frequency of grid voltage. Minimized-sampling period can be obtained from equation (1) as follows:

$$T_{s,FFT} = \frac{1}{f_s} = \frac{T_1}{2N} = \frac{1}{2N \cdot f_1} = \frac{2\pi}{2N \cdot \omega_{r,LPF}} = \frac{\pi}{N \cdot \omega_{r,LPF}} \tag{2}$$

where T_1 is the fundamental period of grid voltage. Using equation (1) and equation (2), N can be given as follows:

$$\frac{1}{T_{s,FFT}} = f_s = 2N \cdot f_1 \geq 2M \cdot f_1 \tag{3}$$

where $T_{s,FFT}$ is the maximized-sampling period. Using equation (3), N can be obtained as follows:

$$N \geq M \ . \tag{4}$$

Detecting the phase shift of grid voltage is essential to the FFT algorithm because it is based on the periodicity of the signal. The phase angle shift of grid voltage produces an error in the phase angle detected by the FFT algorithm. To mitigate this problem in this paper, a selection algorithm is introduced to detect the phase shift in grid voltage. For this purpose, non-periodic index P_ω is defined as follows:

$$P_\omega = 1 - \frac{\omega_{r,SRF}}{\omega_{r,LPF}} . \tag{5}$$

From this index, the selection algorithm is defined as follows:

$$\begin{cases} \theta_{flag,sel} = 1, & \text{if } \left|P_\omega\right| \le \delta_\omega \\ \theta_{flag,sel} = 0, & \text{otherwise} \end{cases} \tag{6}$$

where $\theta_{flag,sel}$ is the detection flag for phase shift and δ_ω is the boundary constant. Using equation (6), the phase angle of grid voltage can be obtained as follows:

$$\begin{cases} \theta_{r,PLL} = \theta_{r,FFT} = \angle E[1], & \text{if } \theta_{flag,sel} = 1 \\ \theta_{r,PLL} = \theta_{r,SRF} , & \text{if } \theta_{flag,sel} = 0 \end{cases} \tag{7}$$

where $E[1]$ represents the fundamental component of grid voltage calculated by the FFT algorithm. Because the grid voltage generally has the half-wave symmetry, the FFT calculation using the data during half-period of grid voltage is enough. As a result, unlike the conventional algorithm requiring full periodic data of grid voltage for FFT calculation, the proposed scheme needs only half periodic data to detect the phase angle of grid voltage.

3 Experimental results

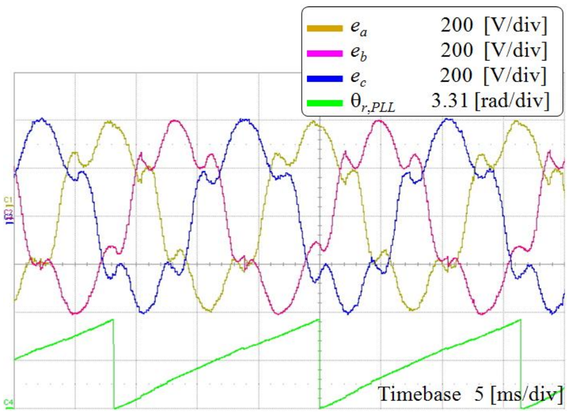

Fig. 1. Experimental result of the proposed algorithm under the harmonic distorted grid voltage.

To verify the effectiveness of the proposed algorithm, experiments are carried out. The highest order of the considered harmonic components is chosen as 8. To satisfy the Nyquist criterion, the minimized-sampling frequency is selected as 16 times of the fundamental frequency of grid voltage. The fundamental frequency is 60 [Hz] and the sampling frequency of the grid connected inverter is set to 10 [kHz].

Fig. 1 shows the three phase grid voltage e_a, e_b, and e_c, and the detected phase angle of grid voltage by the proposed algorithm $\theta_{r,PLL}$. It is observed that the grid voltage is highly distorted by harmonics, including 20% of the 5^{th} harmonics, and 10% of the 7^{th} harmonics. However, the proposed scheme works well even in this condition. Because the grid voltage is periodic, the proposed algorithm selects the phase angle detection based on the half-period FFT. It is shown from this result that the proposed algorithm exactly detects the phase angle of grid voltage even when the grid voltage is highly distorted by harmonics.

4 Conclusions

This paper proposes a novel phase angle detection algorithm based on half-period FFT to improve the performance of phase angle detection even under the distorted grid voltage. It has been proved through the experimental result that the proposed algorithm can detect the phase angle of grid voltage even if the grid voltage is highly distorted.

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